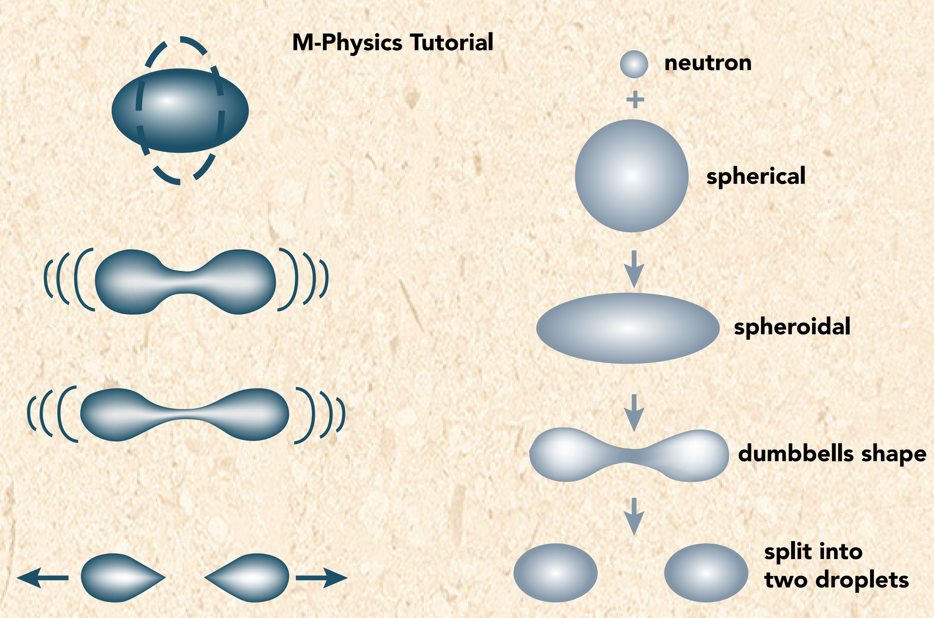
## MODULE VI. 1930-1955

# THE NUCLEUS

We have seen that by 1920, the Bohr theory of the neutral atom with Z negatively charged electrons required a small nuclear core of +Z charge. In 1932, the neutron, the neutral partner of the proton, was discovered. Models for the atomic nucleus consisting of protons and neutrons were quickly developed by Werner Heisenberg and others. By 1934, Enrico Fermi had bombarded heavier elements with neutrons to induce radioactivity in elements of high atomic number. In 1938, Otto Hahn, Lise Meitner and Fritz Strassmann discovered nuclear fission, or the fractionation of uranium nuclei into light elements, induced by neutron bombardment. The discovery of nuclear fission would lead to the development of nuclear power and the atomic bomb by the end of World War II.

## LIQUID-DROP MODEL OF NUCLEUS

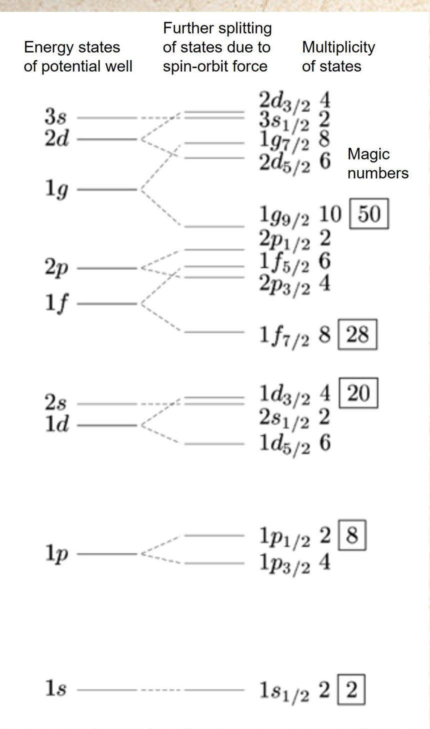
Carl Friedrich von Weizsäckerin 1935 proposed that if the individual nucleons move about within the nucleus much as does an atom of a liquid, one might think of a nucleus as being like a small drop of liquid. Such a model is thus known as the liquid-drop model. Although insufficient to explain all atomic events, the theory underlying the model provides an excellent estimate of the average properties of nuclei. The model accurately describes the atomic mass and binding energies of various nuclei, and predicts radioactivity in the form of emission of alpha and beta particles. The corresponding mass formula is defined in terms of the numbers of protons and neutrons it contains. The original Weizsäcker formula defined five terms:

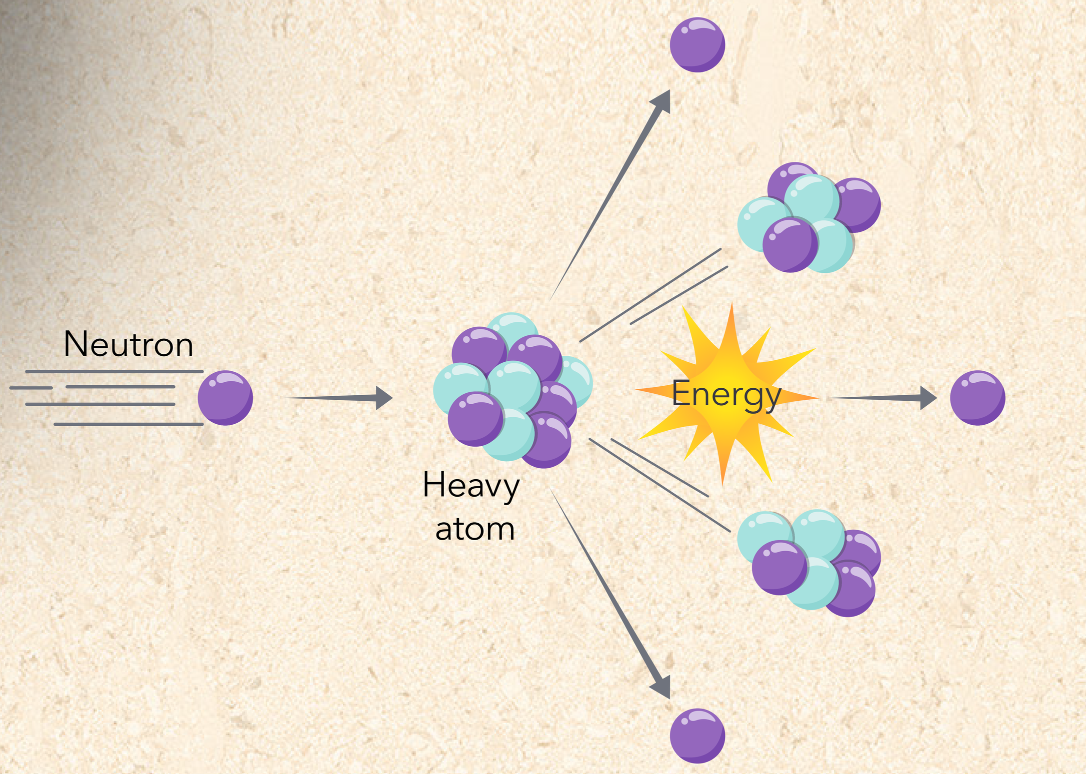



- Volume energy, when an assembly of nucleons of the same size is packed together into the smallest volume, each interior nucleon has a certain number of other nucleons in contact with it. So, this nuclear energy is proportional to the volume
.
- Surface energy corrects for the previous assumption made that every nucleon interacts with the same number of other nucleons. This term is negative and proportional to the surface area, and is therefore roughly equivalent to liquid surface tension.
- Coulomb energy, the potential energy from each pair of protons. As this is a repulsive force, the binding energy is reduced.
- Asymmetry energy, which accounts for the Pauli exclusion principle. Unequal numbers of neutrons and protons imply filling higher energy levels for one type of particle, while leaving lower energy levels vacant for the other type.
- Pairing energy, which accounts for the tendency of proton pairs and neutron pairs to occur. An even number of particles is more stable than an odd number due to spin coupling. In particular, as seen on the right, the liquid drop model provides a good description of the nuclear fission process whereby certain heavy nuclei divide into nuclei of lower mass. If given sufficient extra energy (as by the absorption of a neutron), the spherical nucleus may be distorted into a dumbbell shape and then split at the neck into two nearly equal fragments, releasing energy.

## MARIA GOEPPERT MAYER (1906-1972)

was a German-American physicist educated at Göttingen, where Max Born was her research advisor. She emigrated with herAmerican husband to the U.S. in 1930. For the next 15 years, she held temporary positions teaching and doing research, often without pay. In 1946, she moved to the University of Chicago, where she was appointed Professor in the Physics Department. She also held a position at Argonne National Laboratory. She worked with Edward Teller and Fermi, who provided insight in her work on the development of the shell model. During this time, she developed a mathematical model for the structure of nuclear shells, the work for which she was awarded the Nobel Prize in Physics in 1963, shared with J. Hans D. Jensen and Eugene Paul Wigner. Goeppert Mayer's model explained "why certain numbers of nucleons in the nucleus of an atom cause an atom to be extremely stable"— a phenomenon that had baffled scientists for some time. These numbers, dubbed "magic numbers," represent the protons and neutrons arranged in shells in an atom's nucleus. She was the second woman to receive the Nobel Prize in Physics, after Marie Curie.

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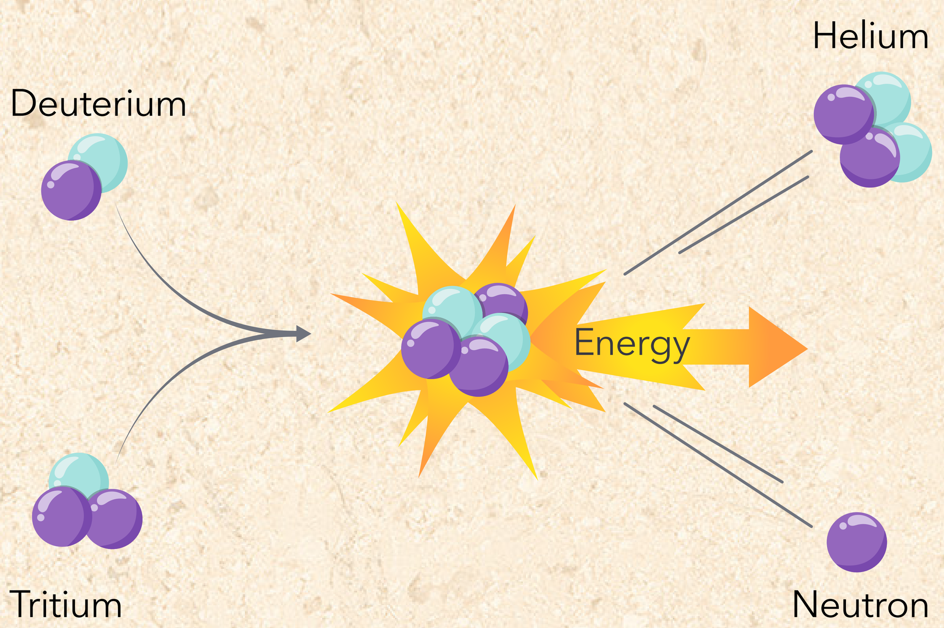
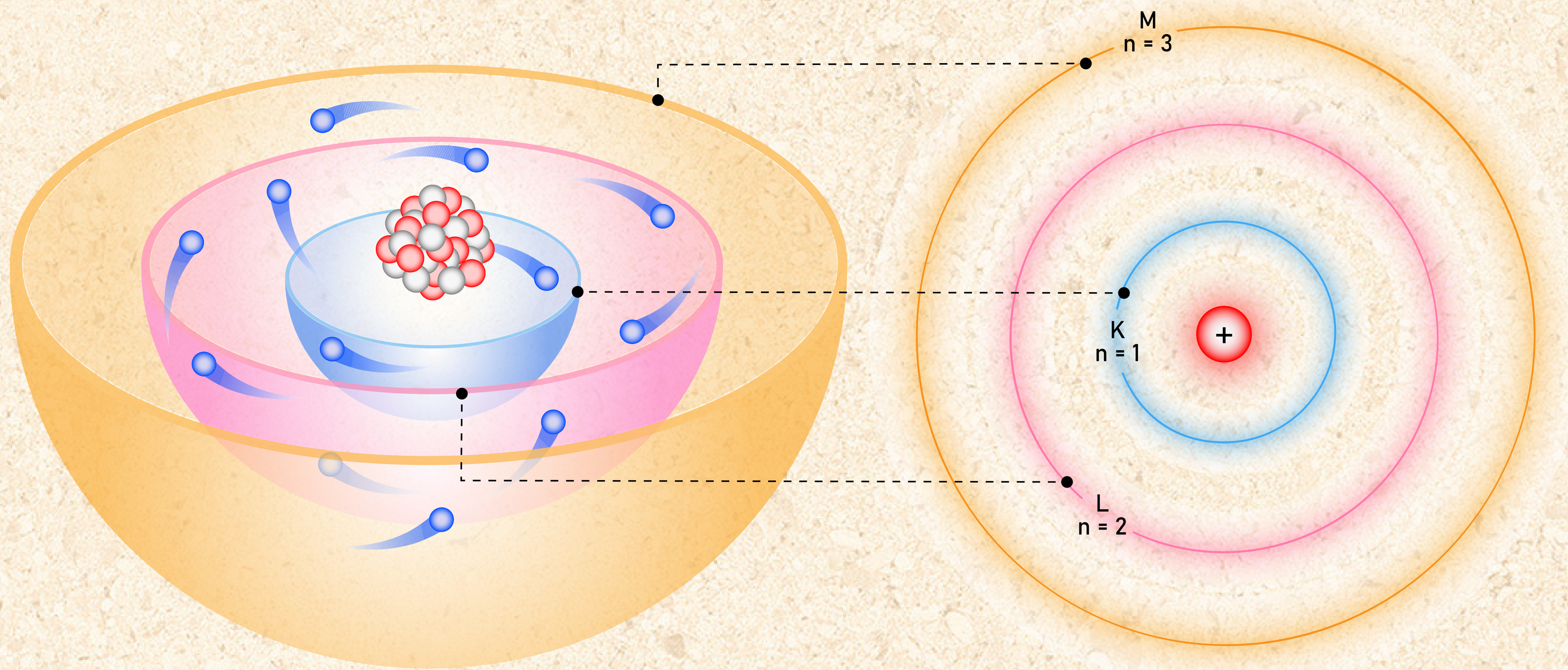



## NUCLEAR FISSION

Nuclear fission sparked a major effort during World War II by the Allies in the U.S. and by Nazi Germany to develop an atomic bomb. The Manhattan Project based at Los Alamos, New Mexico, resulted in successful development of bombs that were dropped on the cities of Hiroshima and Nagasaki in Japan and brought an end to the war. In the mid-20th century, nuclear power reactors based on fission were developed and have produced energy without greenhouse gas emission stably and safely for over half a century. About 20% of electricity in the U.S. is generated by nuclear power. In France and Sweden, about 70% and 40%, respectively, of electricity is generated by nuclear power.

## NUCLEAR FUSION

Large amounts of energy are also generated by the fusion of light nuclei (e.g., deuterium and tritium). For example, the sun's energy is largely generated by nuclear fusion. The difference in mass between the reactants and products is manifested as either the release or absorption of energy. This difference in mass arises due to the difference in nuclear binding energy between the atomic nuclei before and after the reaction. Nuclear fusion is the process that powers active or main-sequence stars and other high-magnitude stars, where large amounts of energy are released. Harnessing fusion energy to generate electricity is a major worldwide research effort as greenhouse gases cause heating of the Earth. There are sizable technical challenges to heat a plasma and confine it in a controlled way such that the fusion energy can be utilized to generate electricity.

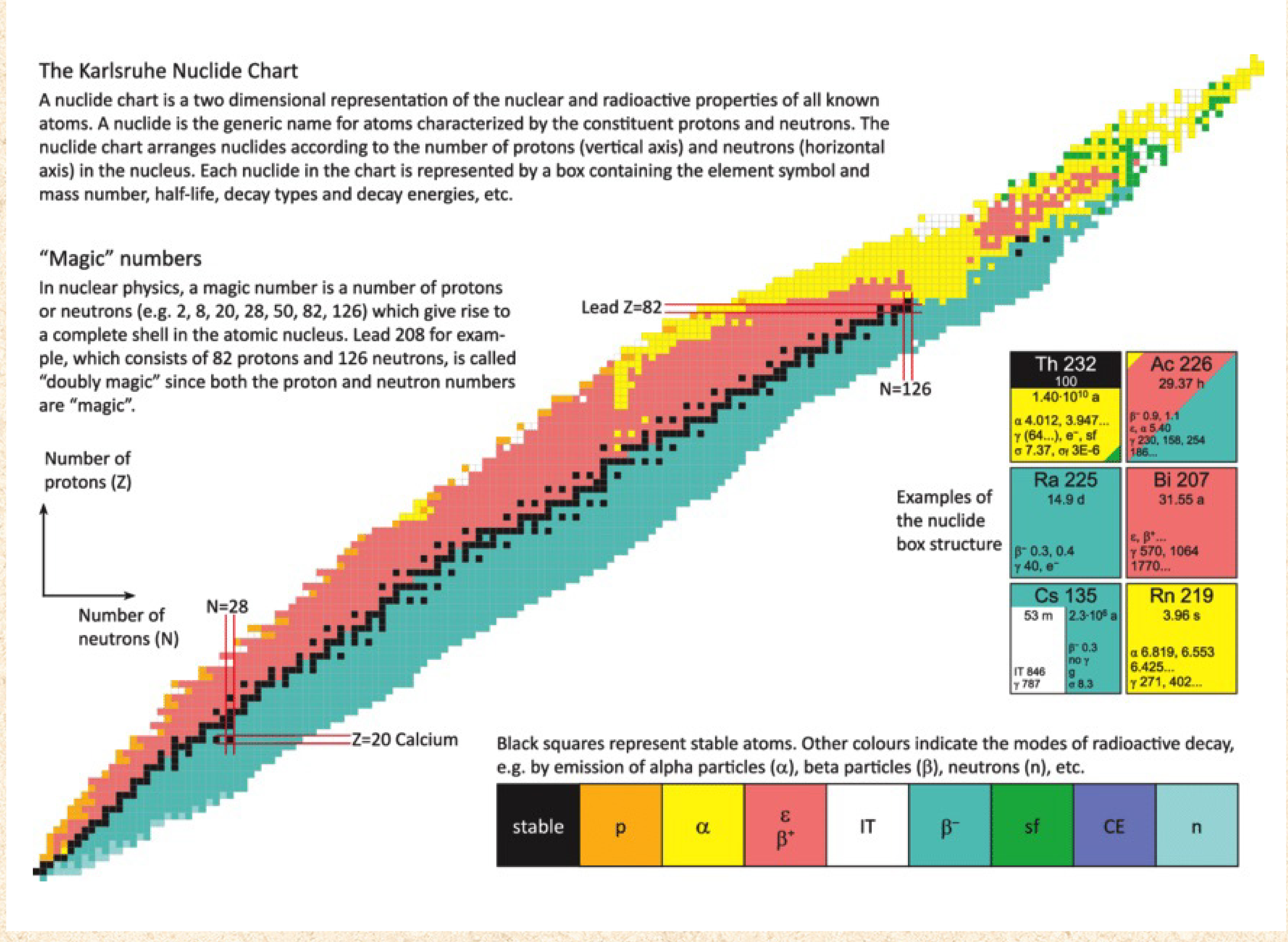



SHELL MODEL STATES

## NUCLEAR SHELL MODEL

The nuclear shell model is a description of atomic nuclei by analogy with the Bohr model of the atom. It was developed independently in the late 1940s by Goeppert Mayer and Jensen. In the nuclear shell model, the constituent nuclear particles are paired neutron-with-neutron and proton-with-proton in nuclear-energy levels that are filled, or closed, when the number of protons or neutrons equals 2, 8, 20, 28, 50, 82, or 126, the so-called magic numbers that indicate especially stable nuclei. The unpaired neutrons and protons account for the properties of a particular species of nucleus as valence electrons account for the chemical properties of the various elements. The shell model accurately predicts certain properties of normal nuclei, such as their angular momentum; but for nuclei in highly unstable states, the shell model is no longer adequate and must be modified.

## CHART OF THE NUCLIDES

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